

MISSION TO PLANET EARTH: PAST PROGRESS AND FUTURE PROSPECTS

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During the 1980's ambitious plans were laid out for the beginning of a new era in Earth studies. Presidential Initiatives in the 1990's created the U.S. Global Change Research Program, including as its largest component, Mission to Planet Earth (MTPE) led by the National Aeronautics and Space Administration (NASA). Mission to Planet Earth efforts are aimed at improving our understanding of the Earth as a system, and our ability to assess and predict the environmental, social and economic impacts of natural and human-influenced processes. The overall goal is to establish the scientific basis for national and international policymaking in response to changes in the Earth system.

The MTPE is primarily focused on obtaining global observations from spaceborne instruments and modeling the Earth as an integrated and coupled system of atmosphere, continents and oceans. MTPE will support focused and exploratory studies of the physical, chemical and biological processes that influence the Earth system. Improvements over current capabilities in the range, detail, and frequency of observations are also needed to develop and test integrated, conceptual and predictive models of the Earth system.

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The initial phase of the MTPE is well underway, with these three tasks integrated within a series of flight missions. The second phase begins in 1998 with the coordination of these tasks within the Earth Observing System (EOS) Program. A major focus of the MTPE/EOS program is to understand the energy and radiation budget of Earth.

Absorption of solar irradiance by the Earth's atmosphere, oceans and surface is the ultimate energy source for the Earth system. For this reason it is important that Earth system scientists develop an understanding of the temporal and spectral variability of solar irradiance and how it is physically related to parameters which describe the system. Measurements of solar variability are especially important during the same time frame in which intensive observations are being made of those system elements which affect the absorption of solar irradiance. The most fundamental of the Earth system observations is the Earth's radiation budget. "Top of the atmosphere" reflected solar and emitted irradiances are inferred from broadband (0.3 to 5.0 μm and 5.0 to 50+ μm) scanning radiometer measurements made from earth orbiting satellites. Estimates of these quantities have been made from the earliest satellites and are a significant component of MTPE/EOS.

Elements of the Earth system with variable characteristics and which most significantly affect the absorption of solar irradiance include clouds, aerosols, water vapor, and surface reflectance. Over the past decade, satellite and surface based instruments have provided estimates of these elements based on remote sensing analyses of the reflected solar and emitted irradiances. Many of these remote sensing approaches assume accurate knowledge of the spectral distribution of the solar irradiance.

Aerosol Interdisciplinary Research Program Workshop
October 30 - November 1, 1995
Columbia, MI)

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Submitted to Bulletin of the American Meteorological Society
May, 1996

1. Introduction

The Aerosol Interdisciplinary Program (AIP) was established by NASA in 1992 to address the suggestion that the direct and indirect radiative effects of sulfate and other aerosols in the troposphere, including those from biomass burning, may be sufficient on a global basis to offset the radiative effects of increases in "greenhouse" gases. Model calculations of these radiative effects have emphasized the importance of understanding the relative contribution of anthropogenic and natural sources of aerosols, transformation and transport processes in the atmosphere, the direct effects of aerosols in the Earth's regional and global radiation budgets, and the interaction of aerosols and clouds in the Earth's radiation balance.

When AIP was formed it was intended that at the end of three years, the investigator team would contribute to a comprehensive scientific assessment of the aerosol issue, including their best understanding of the new information gathered as a result of the research funded under that program. The present workshop is the first attempt to accomplish this assessment and, perhaps more ambitiously to establish the status of our understanding of aerosols in climate. In order to develop this understanding it is necessary to become aware of research sponsored by other US agencies and international organizations. The agenda of the workshop was arranged to give the workshop participants a glimpse of the research supported by other agencies.

Subsequent to that workshop, an extensive report of the AIP investigations has been prepared. The report includes a listing of related research sponsored by several national and international aerosol research programs and satellite aerosol climatology projects, as well as summaries and recommendations of the workshop subsessions. Related programs sponsored by other US agencies include: a task-level listing of the Department of Energy sponsored research on atmospheric aerosols through the Atmospheric Radiation

Measurement program and the Atmospheric Chemistry Program, a similar listing of the 1995 acmsol-related awards by National Science Foundation Atmospheric Chemistry Program, and a table of the University of Miami atmospheric chemistry stations. This extensive report is available through anonymous ftp by taking the following steps:

- 1) "ftp clillatc.gsfc. tlasfi.gel""
- 2) user name: "anonymous"
- 3) password : complete e-mail address
- 4) "cd /pub/chou"

2. Summaries of All' Investigations

The All' investigator team was organized into the following four topic areas:

- Sources of natural and anthropogenic aerosols
- Atmospheric radiation effects
- Atmospheric transport and transformation processes
- Modeling and analyzing global aerosols

The results and accomplishments of the NASA sponsored All' investigations are summarized below relative to the four main topic areas. Coordinators for the topic are given in parentheses following the topic area. AIP investigators whose results are described are also in parentheses located at the end of the description.

a. Sources of Natural and Anthropogenic Aerosols (Coordinator: J. Fishman)

Laboratory studies were conducted to test the combined effects of light and growth rates on the rates of production of dimethylsulfoniopropionate (DMSP) and

1 Dimethylsulfide (DMS) by representative phytoplankton species. Increasing light intensity impacts positively the production rate of DMS by the polar phytoplankton species *Phaeocystis pouchetti*, up to a saturation point for low light adapted cells. For another species, the coccolithophore *Emiliana huxleyi*, no relationship was observed between the production of DMSP and the number of daylight hours, but lowest DMSP production was observed at high growth rates. However, under nutrient-limited conditions, the opposite response was observed: lowest DMSP production at the low growth rates. This is the net effect of such environmental factors on production rates of DMS and DMSP that is observed under natural conditions. (P. A. Matrai)

Laboratory and field experiments were conducted to study the impact of microzooplankton grazing on the cycling of phytoplankton-derived DMSP and its conversion to DMS. Research was focused on two aspects of microzooplankton grazing which were likely to play important roles in the formation of DMS in pelagic and coastal marine environments: grazing of phytoplankton and of bacteria. Laboratory experiments showed that grazing of the phytoplankton *Emiliana huxleyi* 370 by the protist *Oxyrrhis marina* led to the removal of DMSP without production of DMS. Because grazing removes a major fraction of phytoplankton production, this work helped explain why so little DMS appeared to be produced from algal DMSP. On the other hand, *Emiliana huxleyi* 373 appeared to be capable of producing DMS because it contained the enzyme DMSP-lyase. Another pathway for DMS production involving marine bacteria was studied. It was shown that marine bacteria were able to take up and store DMSP from seawater. When bacteria containing DMSP were grazed by flagellates, the DMSP was then metabolized by the grazers. This pathway might also represent an alternative route for metabolism of algal DMSP. (E. Sherr, B. Sherr, G. Wolfe., R. Kiene)

Meteorological and latitudinal effects on DMS concentrations and on the size-dependent chemical, physical, and radiative properties of aerosol particles were studied

from measurements made on two cruises in the mid-Pacific from Gulf of Alaska to Antarctica. The relative number concentration of the modes within the Marine Boundary Layer (MBL) aerosol size distribution was found to depend on regional and mesoscale meteorology. Subsidence of air from the free troposphere to the MBL in the high and mid-latitudes resulted in the injection of ultra-fine particles to the MBL. In the tropics, the aerosol size distribution reflected the growth of particles from the Aitkin to the accumulation mode size range. The fraction of the aerosol mass that was non-sea-salt sulfate aerosol was highest in regions having the longest MBL residence time or the largest sulfur sources. Analysis of the Advanced Very High Resolution Radiometer (AVHRR) data showed reasonable correlation with optical depth measured from the ship. There was a diurnal behavior in aerosol size in the tropics; larger sizes in the morning and smaller sizes in the afternoon. However, no diurnal trends were observed in the optical depth measurements either from ships or from satellite. (T. S. Bates, P. K. Quinn, P. A. Durkee)

The Fire Atmosphere Sampling System (FASS) was used to measure and characterize emissions of particulate matter and trace gases from fires in various tropical ecosystems, ranging from primary forest, slashed second-growth forest, to savanna. Emission factors for the release of CO₂ for burning of savanna, slashed second-growth forest, and primary forest were measured. It was found that emission factors for pasture burns in Brazilian Amazon were about 20% larger than that for savanna burns in Cerrado, Brazil. Areas of savanna burned by fires usually release more than 85% of the total carbon during the flaming phase of combustion. The FASS packages were also used to develop carbon release and emission factors for fires used with shifting cultivation in southern Africa. The active pile burns and burns of the fallow chitemene sites were studied for smoke emissions. (D. E. Ward)

Volcanic aerosol properties were derived from TOMS, AVHRR, and IIRS satellite measurements. The Tropospheric SO₂, clouds produced by the 1984 Mauna Loa eruptions were studied using the TOMS measurements, together with the Correlation Spectrometer data obtained from aircraft traverses through the plume. The volcanic clouds of the 1994 Rabaul eruptions were studied using the AVHRR and TOMS data. Significant quantities of ice in the volcanic clouds were identified from AVHRR radiances. Low SO₂ concentration was measured by TOMS. These results indicated that SO₂ was scavenged through entrainment of seawater in the eruption column; as the column rose, the entrained water froze. Algorithms were developed to determine aerosol masses from IIRS radiances and to differentiate ash and gas volcanic masses from TOMS and AVHRR radiances. (G. J. S. Bluth, L. S. Walter, A. J. Krueger)

A dynamic physico-chemical model describing the formation, evolution, and radiative properties of stratospheric aerosols was developed to study the aerosol formation and growth in volcanic eruption plumes and clouds. It had the capability to treat the sulfur chemistry, the formation and growth of sulfate particles and removal rates of silicates and residual sulfates in volcanic clouds. Studies were conducted at two scales, that of aerosol growth in the whole volcanic plume systems up to the time that the silicate particle cloud disperses by fallout and leaves an aerosol veil, and that of the micro-physical processes of sulfuric acid/acetic growth, both on silicate particle surfaces and by condensation. The model was demonstrated to be capable of simulating the characteristics of stratospheric background and volcanic aerosols. Process studies were conducted to identify the relative importance of chemical and physical mechanisms, such as nucleation, condensation, coagulation, sedimentation, and cloud dispersion on aerosol formation and evolution in volcanic clouds. (S. Self, J.-X. Zhao, R. P. Turco)

Advances were made in carbon isotopic measurements to quantitatively distinguish fossil from biomass sources of carbonaceous gases and aerosols, using the techniques of

Accelerator Mass Spectrometry (AMS) and Isotope Ratio Mass Spectrometry (IRMS). Studies were conducted to apportion carbonaceous aerosols among natural and anthropogenic sources. Results were used to validate transport models (sources-receptor modeling). Research was conducted on long-range transported aerosol, and on carbonaceous aerosol in the polar regions and the cryosphere. The research produced two breakthroughs enhancing the power to apportion fossil and biomass carbonaceous aerosol: (1) successful C-14 "dating" of individual polycyclic aromatic hydrocarbon combustion tracers; and (2) demonstration of a link between patterns of organic combustion products and C-13 combustion isotopic fractionation. (L. A. Currie, J. M. Conny, R. A. Fletcher, G. A. Klouda, R. H. Verkouteren)

b. Atmospheric Radiation Effects (Coordinator: J. Coakley, Jr.)

Measurements were made of boundary layer aerosol size distribution, scattering coefficient, backscatter coefficient, absorption coefficient, and size-dependent composition. Aerosol scattering characteristics were calculated based on the measured aerosol size distribution and were found to be in agreement with the optical properties (scattering and backscattering coefficients) measured *in situ*. Aerosol scattering characteristics were used to calculate the optical depth of the marine aerosol boundary layer, which was then compared to the optical depth derived from spectral differential extinction analyses from both aircraft vertical profiles and multispectral shadowband radiometers located above and below the boundary layer. Both measured and modeled results were found to agree favorably with AVHRR aerosol optical depth retrievals using a new aerosol model. (A. D. Clarke, J. N. Porter)

The cloud droplet and CCN spectra were measured in the summer and winter phases of the Southern Ocean Cloud Experiment (SOCEX). CCN were characterized according to volatility and size vs. supersaturation measurements. Results showed that cloud droplet and CCN concentrations were low in the SOCEX, and there was a decisive difference in

cloud droplet and CCN concentrations between summer and winter. CCN concentrations were more than a factor of two higher in summer than in winter. The width of the CCN distribution in clouds with the vertical liquid water content (LWC) closer to adiabatic values is significantly narrower than that in other clouds that do not have adiabatic LWC values. The size vs. supersaturation measurements were consistent with the volatility measurements. These measurements indicated that the CCN near Australia resemble pure soluble particles. Results of the measurements of cloud droplet size distribution were compared with that of the FIRE and ASTEX. (J. Hudson)

Various source and sink terms of CCN in cloudy MBL was individually and systematically evaluated. Those terms evaluated were: nucleation and depositional growth, fractional activation, vertical and horizontal transport, and sulfate production in haze particles. A numerical model (Lagrangian Transport Model) was developed to permit time integration of the CCN balance equation. This model was used to study the effect of salt particles on the condensational growth of CCN. (M. Baker, D. Hegg)

A new technique based on a combination of spectral and textural measures was developed to detect aerosols over land. The AVHRR data were used to detect aerosols from biomass burning, dust storms, and forest fires. Spectral combinations and the textural feature that could best differentiate aerosol and the underlying background effects were determined. It was found from analyses of many satellite images that the combination of textural and spectral measures was a promising method for aerosol detection over land. Studies of the AVHRR and instantaneous scanner (IRIS) data showed that the aerosols from biomass burning and dust storms (over both land and ocean) had a net radiative impact of cooling ranging from -5 to -77 W m⁻². (S. A. Christopher, R. M. Welch)

The aerosol size distribution, chemical composition, hygroscopicity, and CCN number and supersaturation spectra were measured in four different air masses: tropical oceanic, Arctic haze, clean Arctic, and northern oceanic. A model of cloud activation was

developed to assess the effect of CCN alterations on cloud microphysics. Results showed that the aerosols at M1.0 are monomodal and more volatile than MBL aerosols, which is consistent with predominantly sulfuric acid at M1.0 and ammonium sulfate in the MBL. Arctic haze aerosols have a large refractory fraction and a bimodal distribution with the smaller mode around $0.05\text{ }\mu\text{m}$ dominations. (G. E. Shaw, R. L. Benner)

To determine what subset of aerosol particles actually act as CCN, the characteristics of ambient aerosol particles was compared with that of particles incorporated into marine stratocumulus clouds in the Southern Hemisphere. Marine stratiform clouds were sampled from aircraft off the coast of Tasmania as part of the SOCEX. The DRICCN spectrometer measured ambient CCN spectra, and a counterflow virtual impactor collected and evaporated cloud droplets of different size. It was verified that regions with near-adiabatic LWC near cloud base had residual nuclei spectra that would be expected from adiabatic growth on the below-cloud CCN spectra. Higher in the cloud, residual nuclei spectra were often indicative of entrainment and mixing. Electron microscopic analysis showed that the ambient accumulation and coarse-mode particles are predominantly sulfates with varying degrees of neutralization by ammonia. These particles did not show evidence of internal mixing. (C. Twohy)

Balloon-borne measurements of the aerosol size distribution and chemical and optical properties in the mid- and upper troposphere were made at Wyoming at monthly intervals over a period of 1.5 years. The heated and unheated CN (condensation nuclei) and OA (optical aerosol) measurements were used to estimate the mass fraction of the aerosol volatile at $160\text{ }^{\circ}\text{C}$, while results from comparisons of the nephelometer measurements were used to estimate the light scattering coefficient associated with the volatile aerosol. Results indicated that a significant fraction of the aerosol mass behaved in a manner consistent with that of sulfuric acid, that this fraction increases through the upper troposphere, and that the optical properties of the aerosol were strongly influenced by the sulfuric acid component.

Values of the sulfate scattering efficiency corresponding to the volatilized aerosol mass were also derived. (J. Deshler, J. R. Snider, G. Vali)

A detailed model of the stratocumulus-topped MBL was developed that included aerosol microphysics, turbulent transport and radiative transfer. Model simulations were conducted to study the effect of aerosols on cloud and radiation. The simulations showed that the width of the aerosol size distribution had a large impact on the size distribution of cloud droplets. Simulations also showed that CCN concentrations in the MBL were strongly dependent on their production rate, so that changes in the latter could affect the earth's albedo through the effects of CCN on clouds. (P. V. Hobbs)

Satellite radiance measurements were used to study the impact of fires in South America on cloud microphysical and optical properties. Analysis of the AVHRR data over Amazon forest showed that quadrupling of the column concentration of smoke from background values increased the reflectance from 0.35 to 0.45 and decreased the effective drop size from 12 μm to 8 μm for low clouds. However, no significant effect of aerosol on cloud microphysics or on cloud reflectance was found over the drier Cerrado region. The results demonstrated the transition of smoke effect from an increase in cloud reflectance due to modification of cloud drop size for thin clouds to a decrease in cloud reflectance due to absorption by the black carbon in the smoke for thick clouds. (Y. J. Kaufman, L. A. Remer, R. S. Fraser, B. N. Holben)

Vertical variations in aerosol mass extinction coefficients and in size-dependent aerosol microphysics and chemistry were both measured in the MBL of the polluted North Atlantic. Humidity dependent comparisons between the measured and calculated aerosol extinction coefficients showed good agreement. The mass scattering coefficient expressed per mass of sulfate was found to vary between 5 and 16 $\text{m}^2 \text{g}^{-1}$. Measurements were also made through a Saharan dust layer located above a polluted boundary layer. The mass scattering coefficient for the dust was estimated at 1.1 $\text{m}^2 \text{g}^{-1}$. Both pollution and dust

layers below 4 km contributed similarly to aerosol optical depth that totaled about 0.35 for this region. Other measurements in the clean North Pacific have found representative boundary layer optical depths to be on the order of 0.1 with similar contributions from sea-salt and sulfate to column optical depth. (A. D. Clarke, J. N. Porter, F. P. J. Valero, P. Pilewskie)

c. *Atmospheric Transport and Transformation Processes* (Coordinator: B. Toon)

Laboratory measurements were made of the H_2SO_4 vapor pressure above aqueous sulfuric acid droplets and above aqueous $(\text{NH}_4)_2\text{SO}_4/\text{H}_2\text{SO}_4$ mixtures at relative humidities ranging from 2.1020 %. These measurements showed that the equilibrium H_2SO_4 vapor pressure is relatively unaffected by the presence of ammonium for the ammonium to sulfate molar ratio less than about 0.5; at this point the H_2SO_4 vapor pressure drops precipitously by about three orders of magnitude. Field measurements at Mauna Loa, Hawaii and Idaho 1 Hill, Colorado showed that OH , H_2SO_4 , and ultra-fine particles followed regular diurnal profiles. There was systematic correlation between H_2SO_4 and ultra-fine particles, suggesting the participation of H_2SO_4 in the nucleation process. New particles were routinely observed at sulfuric acid concentrations that were one to two orders of magnitude below the levels predicted by the binary $\text{H}_2\text{O}/\text{H}_2\text{SO}_4$ nucleation. Observed rates of particle production varied roughly as $[\text{H}_2\text{SO}_4]^2$, suggesting a collision controlled process for nucleation. (P. H. McMurry, F. L. Biscle)

Molecular-based and parameterized methods for representing aerosol processes and properties were developed and tested. Time-dependent and steady-state solutions were obtained for sulfuric acid nucleation, permitting description of the evolution of cluster number density and composition throughout the nucleation process. A general analytic representation was given of the free energy surface governing cloud droplet activation, leading to characterization of fluctuations in drop size at the boundary between stable and unstable Köhler regimes and thereby permitting evaluation of the statistical effects of CCN

concentration and properties on the number of particles activated and on the cloud droplet size distribution. Representation of aerosol evolution and optical properties in terms of the moments of the radial size distribution appeared to be an accurate and efficient approach to description of aerosol processes and properties in complex flow fields. (S. E. Schwartz, R. L. McGraw)

Improvements were made to the laboratory experimental techniques for studying heterogeneous kinetics involved in gas-to-particle conversion processes. Laboratory measurements were used to determine Henry's law solubilities and Setchenow coefficients of reduced sulfur species, the temperature dependent accommodation coefficient of ammonia (NH_3) on water, and the acid catalyzed hydrolysis of formaldehyde (CH_2O) in acidic solution. Both NH_3 and CH_2O uptake have been measured over the acidities varying from concentrated H_2SO_4 to pH 13 water. The uptake results were modeled using chemical activities, diffusion coefficients and Setchenow coefficients. (D. R. Worsnop, J. 'J'. Jayne, C. E. Kolb)

Shipboard measurements in the equatorial Atlantic were made to link DMS emissions to the generation of sulfate aerosol within the MBL. It was found that the diurnal variation of DMS oxidation differed with theoretical predictions made on the basis of traditional OH radical attack which peaks at noon. Some features of the diurnal cycle indicated the need for a morning reaction for DMS, and possibly also for an afternoon reaction. It was suggested that the Cl atom radicals has a very rapid reaction with DMS. The Cl radicals could account for the rate of consumption of DMS in the morning and late afternoon hours. (R. B. Chatfield)

A detailed box model was developed to simulate the formation, growth, and removal of sulfate aerosols in the MBL. The relation between *in situ* sulfate particle production and growth and the CN and CCN number concentrations in the marine boundary layer was examined. The mechanism of the OH-initiated oxidation of DMS was investigated by

using sulfur field datasets from the Pacific and Antarctic. The GFDL global chemistry and transport model was used to simulate the present-day distribution of anthropogenic sulfate. Model results agree reasonably well (within a factor of 2) with observations from North America. The model was also used to investigate the factors governing the seasonal evolution of the anthropogenic sulfate burden in various regions of the Northern Hemisphere middle latitudes. (P. Kasibhatla, W. L. Chameides, D. Davis)

Measurements during the Lagrangian evolution of a polluted aerosol column over the Atlantic demonstrated that decreases in column concentrations were accounted for by entrainment of clean air into a diverging polluted boundary layer flow. A time series of measurements at a pristine location in the equatorial Pacific (Christmas Island) demonstrated that the clean marine boundary layer size distribution could be explained by subsidence entrainment of "new" nuclei from the free troposphere followed by heterogeneous growth, probably enhanced by non-precipitating cloud cycling. Both observations emphasized the importance of including the dynamic coupling of the boundary layer with the free troposphere in order to interpret the evolution of the aerosol size distribution and related properties. (A. D. Clarke)

d. *Modeling and Analyzing Global Aerosols* (Coordinator: A. Robock)

A 5-year dataset of the Normalized Difference Vegetation Index (NDVI) was derived from ISCCP CX radiances. The NDVI was used to relate different ecosystem with cloud properties. Results showed that NDVI had a positive correlation with cloud effective radius and cloud cover for most regions. The possible mechanism involved was that vegetation played a role in increasing water vapor content and decreasing aerosol amount in the air. The indirect effect of aerosol on cloud albedo was estimated. It was found that at the 0.99 significant level, clouds in the Southern Hemisphere had larger droplet sizes than did clouds in the Northern Hemisphere. The temporal correlation between the effective

cloud radius and albedo showed that clouds over about 20% of the earth's surface were susceptible to the aerosol indirect effect. (Q. Han, R. M. Welch, W. B. Rossow)

The vertical profiles of extinction coefficient measured by the Stratospheric Aerosol and Gas Experiment (SAGE II) and the aerosol optical thickness derived from AVHRR radiances were used to determine the contributions of lower tropospheric (below 6 km altitude), upper tropospheric, and stratospheric aerosols to the total aerosol optical thickness. The analysis was performed for the eight seasons prior to the eruption of Mt. Pinatubo and for nine different regions over the global oceans. In most cases, the combined optical thickness of the upper troposphere and stratosphere was less than 0.01. It was concluded that, during volcanically-unperturbed periods, the direct aerosol radiative forcing is dominated by aerosols in the lower troposphere. (J. A. Ogren, D. J. Hofmann, R. S. Stone)

GOES-7 and GOES-8 visible and multi-spectral infrared data were used to document daily biomass burning activities in South America and to distinguish smoke/aerosol from other multi-level clouds and low-level moisture. The areal extent and transport of smoke/aerosols throughout the region and over the Atlantic Ocean for the 1988 and 1995 biomass burning seasons were catalogued. The temporal resolution of the GOES data made it possible the determination of the prevailing circulation and transport of aerosols by considering a series of visible and infrared images and tracking the motion of smoke, haze, and adjacent clouds. (W. P. Menzel, E. M. Prins)

The sources, sinks, and transport of desert dust were investigated by using the GISS tracer model. Dust emission was parameterized in terms of soil moisture, surface wind speed, soil texture, vegetation, and soil surface conditions. The output from the tracer model in terms of the spatial and temporal distributions of aerosol was then used as input to the GCM to examine aerosol forcing. Based on the model results, the global mean net radiative forcing due to wind-blown mineral dust was estimated to be $+0.14 \text{ W m}^{-2}$ at the

top of the atmosphere, but -1.0 W m^{-2} at the surface. Thus, mineral aerosols alter the atmospheric stability resulting in a more complex climate forcing than due to sulfate aerosols. Results from GCM simulations showed that the direct forcing of tropospheric sulfate aerosols alone was insufficient to account for the observed global changes in diurnal temperature range. (B. B. Carlson, J. Fung, J. E. Hansen, A. A. Lacis, L. D. Travis, M. Mishchenko)

Estimations were made of the total emissions and concentrations of sulfate and carbonaceous aerosols so that the direct forcing of climate can be estimated. To estimate the aerosol indirect forcing, a method was developed for estimating the change in cloud droplet concentrations from increasing concentrations of CCN. Global-mean direct radiative forcing of anthropogenic sulfate aerosols was estimated to be $\approx -0.9 \text{ W m}^{-2}$, but the magnitude of the forcing is highly dependent on the relative importance of the gas phase and aqueous phase production mechanism. It was shown that a total forcing of this magnitude is large enough to significantly impact climate and the predicted patterns of temperature change. Using a method of pattern correlation, the total forcing by anthropogenic aerosols associated with industrial emissions was in the range from -1.2 to -2.4 W m^{-2} . (J. B. Penner)

The PNL (Battelle Pacific Northwest Laboratories) global chemistry model was coupled to the PNL version of the NCAR CCM2 to estimate the direct and indirect radiative forcing due to anthropogenic sulfate aerosols. The aerosol radiative properties were parameterized using Kohler and Mie theory to calculate the direct radiative effects. Kohler theory was used to determine the equilibrium size of an internal mixture of aerosol components as a function of relative humidity. Results showed excellent agreement between the Mie calculations and the parameterization for a variety of aerosol species, for relative humidity ranging from 0 to 90%, and for surface mode radius ranging from 0.01 to $1 \mu\text{m}$. (S. J. Ghan, R. C. Easter, L. R. Leung, Y. Zhang, R. Saylor, L. Peter, R. Zaveri)

3. Workshop Recommendations

Studies of aerosol climatic effects can be addressed from two different perspectives: evaluations of the effect of aerosols on current climate, and predictions of anthropogenic aerosol effect on future climate. The former requires information on the three-dimensional global distribution of aerosol optical properties, while the latter requires the knowledge of emission, transformation, transportation, as well as chemical, physical and optical properties of aerosols. Therefore, the study of the aerosol-related climate problem is inherently interdisciplinary. The workshop recognizes and recommends that

- Further laboratory and field work are needed to study the emission sources and physical, chemical, and isotopic transformation of aerosols and their precursors.
- Regional and seasonal aerosol distributions are crucial to the study of aerosol climatic effect. These distributions can be most effectively derived from concerted surface, airborne, and satellite measurements.
- Field campaigns emphasizing the closure (consistency) among aerosol vertical distribution, chemical, physical, and optical properties, and radiative fluxes are critical in understanding and validating aerosol radiative forcing.
- Enhanced airborne measurements of aerosol and cloud particles are needed to advance our knowledge of the effect of aerosols on cloud microphysical and optical properties.
- Large-scale vertical distribution of aerosols can be reliably derived from space-borne lidar measurements, which are essential in mapping three-dimensional global aerosol distributions.

- Retrieval of global distribution of aerosols can be optimized by synthesis of multi-sensor satellite observations, such as AVHRR, SAGE II, TOMS, as well as next generation sensors, such as MODIS, MISR, and EOSP.
- Process-oriented chemical, micro physical, and optical modeling at regional scales are essential to developing parameterizations for use in GCM's.
- Developments of GCM's which include aerosol emission sources, and transformation and transport processes are in urgent need for the assessment and prediction of the aerosol climatic impacts.
- There is a need for tight coordination between climate modeling and measurements to optimize multivariate aerosol observations for applications to climate models. Guidance from climate modelers is required in design of measurement strategies.
- compilations of aerosol data bases are needed so that they can be more easily accessed by the scientific community.
- The interdisciplinary nature of the aerosol-climate problem requires coordination and collaboration of national and international programs and agencies.

Acknowledgments

The workshop agenda was developed through collaboration with colleagues: Dr. Jack Kaye, NASA Headquarters; Dr. Ken Bergman, NASA Headquarters; Dr. M. Patrick McCormick, NASA Langley Research Center; and Professor Robert Charlson, University of Washington.